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SUSTAINABLE ECONOMIC DEVELOPMENTS IN THE AUSTRALIAN ENERGY SECTOR: FINDINGS OF THE AUSTRALIAN ENERGY PLANNING SYSTEM OPTIMIZATION MODEL (AEPSOM)

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Abstract—A multi-level optimization (MLO) model is used to study some of the energy issues pertinent to Australia's situation. These issues include self-sufficiency, conservation, sustainability, etc. This paper is an outline of the Australian Energy Planning System Optimization Model (AEPSOM) and the policy implications derived from the solution of this model. The model results suggest two important policy strategies for sustainable development of the energy sector: reduction in the use of energy and development of environmentally sound and renewable energy technologies. These changes are in the directions required for sustainable energy sectoral development in Australia. © 1998 Elsevier Science Ltd.

1. INTRODUCTION

Energy plays a very significant role in the operation and maintenance of the ecosystem. The role of energy in the production processes in the economy is more evident [1]. Energy along with land and capital is a necessary and integral factor input in virtually all economic activities in society, and to a certain extent is also an indication of the level of such activities. However, energy use in the production process has contributed, by way of residual outputs, to the environmental degradation and unsustainability of the economy. In addition, most of the energy sources currently in use are non-renewable and will inevitably be exhausted. Hence, the two major issues regarding energy in the sustainability debate are its environmental impacts and energy resource conservation.

Australia's oil supplies are expected to be depleted in about 30 years, with serious implications for suppliers, consumers and the sustainability of energy resources. Therefore, there is a need to plan for and develop a sustainable energy sector. Several studies, such as that by Dovers [1], exist but they do not provide a policy tool that can be used to drive energy policy towards a sustainable outcome. This paper addresses the issues surrounding energy policy and sustainable energy development within a policy optimization strategy. This paper develops an optimizing multi-level programming (MLP) model to study the

energy sector. A special feature of this paper is the investigation of the consistency of policies and strategies adopted in the 1980s with those required for a sustainable development of the energy sector.

2. SUSTAINABLE DEVELOPMENT OF THE ENERGY SECTOR

The "Bruntland Report" has defined, among other literature in this area, sustainable development as development that satisfies the needs of current and future generations [1]. This alludes to the view that the continuation of the industrialization strategies of the last 200 years to maintain the welfare of current generations will be detrimental to the welfare of future generations. The world's environmental stocks may further be degraded by maintaining or increasing the rate of extraction of non-renewable energy resources for economic production and consequently increasing the rate at which pollutants are introduced into the environment [1]. A mathematical statement of sustainable development of a sector involves finding the solution to the optimization problem [2]:

$$\text{Max} \int_{t=0}^{\infty} e^{-\rho t} U(C,X)\mathrm{d}t$$

subject to $X = a[Q(X) - N(C)]$, $X(0) = X$, $X(\infty)$ free.

Sustainability requires that the dynamic economy/sector ensures $W = A$ and $(R + E) = G$ so that the economy produces zero environmental degradation and loss in productive capacity in the economy. (Definitions of the symbols are: X = level of environmental quality, C = consumption, W = waste emitted from the economy, A = waste assimilated in the economy, R = flow of renewable resources, G = biological productivity of these resources, E = flow of exhaustible resource and a = environmental quality coefficient.)

The definition of sustainable development given above is static in the sense it limits the economy within the present level of capital stocks and technological development. The composition of production and consumption may change as their levels increase and capital substitution for energy inputs and waste recycling may also mitigate the detrimental effects of higher economic activity [1]. Therefore the analysis is reduced to the determination of the magnitudes of these two effects in relation to the overall industrialisation process, and the facilitation of appropriate substitution among capital, labour and non-renewable energy supplies. Another factor to consider is the scope for substitution between renewable and non-renewable energy supplies. There is a view that the use of renewable energy supplies can alleviate the problem associated with finite supplies of non-renewable energy sources, and that they also produce less environmental pollutants [1]. However, this is not generally true for all renewable energy sources, and the scope for this substitution is limited. Hence the issue of energy conservation arises which is a matter of the efficient use of the existing stocks of energy inputs with the possible substitution of capital inputs.

3. CONDITIONS FOR SUSTAINABLE DEVELOPMENT OF THE AUSTRALIAN ENERGY SECTOR

During the last century, the major energy sources in Australia were wood, human energy and draught animals, and subsequently, coal and steam-power [1]. In the early part of this

century, coal, oil and electricity were in substantial use. Gas became a significant energy source in the 1970s. Black coal and uranium are currently exported by Australia [1].

The factors that contributed to the demand for energy in the last four decades were: the higher rates of population and economic growth; the rise in energy exports; the unchanged imports of oil; and the discoveries of new sources of energies [1]. Most of the changes in the energy sectors in Australia occurred in the recent past [1].

Energy end uses comprise mostly of oil, natural gas and electricity, with the industry and transport sectors comprising most of the end users [1]. While the total energy reserves in Australia are abundant given its population size, the reserve of oil is very low, and the increased demand for energy has problems of environmental degradation (environmental pollution, GHG emission, waste disposal, and land degradation) and resource scarcity [1].

Globally and nationally, there is more or less a consensus that the current patterns of energy use cannot continue, but there is disagreement on the desired path of adjustment [1]. During the international meeting in Montreal in 1988, the Australian Government agreed to reduce GHG emissions by 20% between 1988 and 2005 [1]. World population is expected to stabilise at about 8–14 billion during the next century, with the developing countries contributing a large portion of that growth. This will inevitably imply higher world energy demands. Even though the long term projections into the next century are fraught with uncertainties, policies will need to be developed to address the increase in energy demand and the likely environmental consequences of such increases.

The two conditions required for a sustainable energy policy are "*energy conservation*—the reduction of the amount of energy required to produce required goods and services"—and "*new or alternative sources of energy* that avoid or minimise the problems associated with the present fossil-fuel-based system" [1].

4. POLICY OBJECTIVES IN THE 1980s

The policy problems for the Australian economy are: Australia's self-sufficiency in energy, the appropriate pricing of energy products, the choice of fiscal instruments, the distributional equity of the benefits created in the energy sector, the conservation of energy (particularly of fossil fuels), the search for measures to manage supply disturbances, the optimum depletion rate of fossil fuels, and the determination of the exact boundary of energy policies [3, 4].

5. A MULTI-LEVEL POLICY MODEL TO STUDY SUSTAINABILITY

Energy models and planning studies that have been conducted in Australia and overseas only have one level of optimization [5]. These studies cannot adequately represent the underlying multi-level policy system in a mixed market economy like the Australian economy. The interaction between the government policy and the economic agents' decision making is missing. Consequently, existing energy models cannot provide results to facilitate the decision making process, and may not be satisfactorily applied to formulate multi-level energy planning policy.

Economic decisions in the mixed market economy are made by individual economic agents (the producers and consumers of energy), while policy makers only influence the behavior of these economic agents. The policy makers decide the optimum policy for the government (*the policy problem*), and the economic agents decide the optimum production

and end-use of the energy products given the government's policy (*the behavioral problem*). The behavioral problem is embedded in the policy problem, so that the economy is represented by a two-level policy system. The Multi-level Optimization (MLO) addresses these two problems jointly in the optimization and produces the optimized policy decision set to facilitate decision making.

An empirical MLO energy sector model termed as the Australian Energy Planning System Optimization Model (AEPSOM) developed by the author [6] is used in this study.

An abstract representation of the MLO model AEPSOM is reported below:

$\underset{\{\pm T\}}{\text{Min}}\ WL = wG$ (a)	Policy objective function
Subject to:	
$G = I_1 Y_S + I_2 X_S + I_3 Z_S$ (b)	Definitional equation
$T_1 \leq \pm T \leq T_p$ (c)	Policy constraint
$\{(+T_1)Y + (+T_2)X + (+T_3)Z\} - \{(-T_1)Y + (-T_2)X + (-T_3)Z\} \geq 0$ (d)	Budget constraint
$\text{Min}\ C = (c_1 \pm T_1)Y + (c_2 \pm T_2)X + (c_3 \pm T_3)Z\ \{Y, X, Z \mid \pm T\}$ (e)	Behavioral objective function
Subject to:	
$Z \geq \bar{D}$ (f)	Demand constraint
$Z = \bar{X}$ (g)	Intermediate energy balance constraint
$X = by$ (h)	Energy supply balance constraint
$Y \leq \bar{Y}$ (i)	Resource constraint
$X \leq \bar{X}$ (j)	Capacity constraint
$G, Y_S, X_S, Z_S, Y, X, Z \geq 0$ (k)	Non-negativity constraints

where

WL = value of policy objective function;
w = a vector of coefficient of the policy objective function $(1 \times e)$;
G = a vector of energy target variables $(e \times 1)$;
Y = a vector of primary energy $(p \times 1)$;
X = a vector of energy products $(n \times 1)$;
Z = a vector of end-uses of the energy products $(m \times 1)$;
$\bar{D}$ = a vector of end-uses in different sectors $(q \times 1)$;
c_1, c_2, c_3 = costs of supplying, converting and using energy $\{(p \times 1), (n \times 1), (m \times 1)\}$;
$\pm T_1, \pm T_2, \pm T_3$ = vectors of different taxes and subsidies $\{(p \times 1), (n \times 1), (m \times 1)\}$;
a, b = matrices of technological coefficients $\{(m \times n), (n \times p)\}$;
Is = identity matrix (some of the elements of the diagonal matrix may be 0);
Y_S, X_S, Z_S = sub-vectors of Y, X, Z;
$\bar{Y}$ = a vector of the fixed amount of available primary energy $(p \times 1)$;
$\bar{X}$ = a vector of the fixed level of capacities $(n \times 1)$.

AEPSOM is an MLO partial equilibrium energy sectoral micro-economic planning model. The energy planning problem is modelled in such a way that the policy objective

function is optimized subject to (i) the constraints on and the consequences of the policy options and (ii) the constraints imposed by the behavioral sub-model on the degrees of freedom of the policy makers. The model has four main components: (i) a weighted policy objective function containing the objectives of the policy makers; (ii) the constraints on the choice of policy instruments; (iii) the objective functions of economic agents; and (iv) the constraints on the behavior of economic agents.

The government determines a set of policy instruments and strategies that are constrained by the limits on the variation of taxes-subsidies and by the condition that net government revenue should be positive. The energy behavioral model represents the choice problem of economic agents subject to the energy resource supply, capacity and demand constraints.

AEPSOM was developed on the basis of the following specification of the Australian energy policy planning problem.

1. *Energy Policy Objectives.* Despite the relatively late formalization of Australian energy policy activities, the objectives of contemporary policies have become somewhat more apparent. Some energy policy objectives are commonly found in official government documents and academic work, and these suggest that the major objectives of the Australian energy policy are: the security of energy supply and import independence, the conservation of energy (particularly of oil), the efficient allocation of energy resources, and the equity in income and uses of resources in the energy sector.
2. *Energy Policy Instruments.* The possible energy policy instrument alternatives in Australia are listed as follows:

   (a) Indirect Control: (i) Taxes and subsidies; (ii) Government expenditures for energy conservation, research and development; and, education and information.

   (b) Direct Control: Pricing of domestic crude oil.

   (c) Energy Policy Strategies/Policy Guidelines: (i) Technological strategy; (ii) Depletion policy; (iii) Exploration and development strategy.

6. DATA, SOLUTION AND RESULTS

AEPSOM was specified for the years 1979–80 and 1989–90. Some of the data were estimated by the author and some were obtained from published sources.

AEPSOM was numerically implemented as an MLP model, considered as a collection of nested optimization problems at different levels [9]. The main difficulty with an MLP model is its implementation by an algorithm as it is a recently developed mathematical programming technique. Experiments are still going on to develop an algorithm to solve an MLP. In most of the existing MLP algorithms, the MLP solution is relatively difficult as in these algorithms because some transformation of the original problem is necessary. This makes the size of the transformed MLP large in comparison with the original problem. Also these algorithms are usually not commercially available.

To overcome these problems, the Parametric Programming Search (PPS) algorithm was developed in this study. In the PPS algorithm, the lower level problem of a complete MLP problem is solved as a parametric programming problem. Alternative optimum (basic) solutions to the lower level problem are searched to find the one that optimizes the policy objective function and satisfies the policy constraints. AEPSOM results produced by the PPS algorithm are close to the expected optimum results. Criteria such as efficiency in CPU

time, and cost and efficiency in the extension and transfer of the algorithm were applied to test the algorithm. The algorithm was found satisfactory.

The expected outcome of the modelling work was a set of results for providing guidelines for the formulation of policies. AEPSOM results provided a set of information for an analysis and understanding of the Australian energy policy problems. It also provided results that are capable of addressing energy policy issues in the areas of energy taxes and subsidies, pricing, energy technology, conservation, education and information, research and development, optimum depletion of exhaustible resources, and the exploration and development activities of the government.

For testing the reliability of the AEPSOM results the following conventional validation tests were performed: *a priori* justifications of the relevance of the model; the underlying problems or systems; usefulness of output for achieving the objectives of the modelling study; accuracy of results; comparison of the model results with results of other studies: and, intuitive judgments.

AEPSOM results generated a numerical policy system in the Australian energy sector that has provided some insights into the characteristics of multi-level, multi-goal hierarchical policy formulation in the energy sector. The results have established some analytical aspects of the multi-level decision making process: the need for the determination of the optimum level of policy intervention ($\pm T$); the possibility of the formulation of an improved plan by the government; and the conflicting interests of the government and private sector economic agents.

AEPSOM results have been used to formulate a multi-level optimum energy plan for Australia, details of which are reported below.

7. THE SUSTAINABLE ENERGY SYSTEMS SUGGESTED BY THE MODEL

The following list shows the energy supplies, production and end-uses of the behavioral model, and the variables representing these activities:

Primary Energy Resources

R_1 = coal
R_2 = crude oil
R_3 = natural gas
R_4 = hydro-electricity
R_5 = biomass
R_6 = solar
R_7 = uranium
Ie_1 = imported crude oil

Intermediate Energy

E_1 = electricity from coal
E_2 = electricity from petroleum products
E_3 = electricity from natural gas
E_4 = hydro-electricity
x_1 = coal
x_2 = petroleum products

x_3 = natural gas
x_4 = total electricity production
x_5 = biomass
x_6 = solar
x_7 = uranium

Energy End-uses
Manufacturing Industry Sector:

d_1 = coal
d_2 = petroleum products
d_3 = natural gas
d_4 = electricity
d_5 = biomass

Agricultural Sector:

d_6 = petroleum products
d_7 = electricity

Transport Sector

d_8 = petroleum products
d_9 = electricity

Domestic and Other Sectors

d_{10} = coal
d_{11} = petroleum products
d_{12} = natural gas
d_{13} = electricity
d_{14} = biomass
d_{15} = solar

Exports

Ee_1 = coal
Ee_2 = petroleum products
Ee_3 = uranium

Various versions of AEPSOM were solved and provided different solutions for the flow of the variables listed above. Tables 1 and 2 in the Appendix show the results from variants of AEPSOM.

The technological pattern implied by the results is:

1. The results suggest that imported crude oil (Ie_1) is more attractive than domestic crude oil (R_2).
2. Natural gas (x_3) for intermediate energy is not viable in Solutions 5 and 6, although its use for electricity production (E_1) was justified and its optimal use in 1989–1990 is substantially higher than its actual use.
3. End-uses not chosen by AEPSOM Solutions 5 and 6 in 1979–1980 are: petroleum products (d_2) and natural gas (d_3) in the manufacturing industry sector, electricity (d_9)

in the transport sector, and petroleum products (d_{11}), natural gas (d_{12}), biomass and solar energy (d_{13}).

4. During the decade of the study, the implied technological pattern changed substantially. Solar energy was viable in 1989–90 but not so at the start of the decade. More use of natural gas was suggested at the end of the decade as opposed to coal. Lastly, biomass appeared at the end of the decade but not at the start.
5. The selected end-uses of energy varied with the assumptions made about AEPSOM. The following end-uses were not selected by any of the five models [7].
   (i) petroleum products in the manufacturing industry sector,
   (ii) electricity in the transport sector, and
   (iii) petroleum products in the domestic and other sectors.

8. CONCLUSIONS

The energy system suggested by AEPSOM is consistent with the two conditions of sustainable development mentioned above. In addition, the AEPSOM results show that energy conservation implies the same policies as ecologically sustainable development. In other words, if energy conservation policies are implemented they will consequently be ecologically sustainable. Less use of coal as an energy source is suggested by AEPSOM. This is also consistent with the aim of lowering GHG emissions. Hence no extra costs to the economy are incurred by the goal of lowering GHG emissions if energy conservation policies are put in place.

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APPENDIX

Table 1.Optimum Activities for AEPSOM (PJ)* 1979–1980

Energy Type	1979–80 Actual **	Model Results		
		Model No.1	Model No.2	Model No.5
R_1	2448.81	2448.8101	2448.8101	2938.5703
R_2	874.87	874.8701	874.8701	0.0000
Ie_1	435.34	453.3918	453.3918	1709.4453
R_3	364.18	364.1799	364.1799	437.0100
R_4	50.23	86.6099	86.6099	103.9300
R_5	138.14	138.1399	138.1399	165.7600
R_6	0.50	0.0000	0.0000	0.0000
R_7	586.04	586.0400	586.0400	703.2400
E_1	845.57	351.6301	351.6301	864.0101
E_3	87.91	364.1799	364.1799	0.0000
E_4	50.23	86.6103	86.6103	103.9304
x_1	493.95	2097.1797	2097.1797	2074.5601
x_2	1188.82	1063.2300	1063.2300	1275.9099
E_2	50.23	265.0317	265.0317	433.5352
x_3	251.16	0.0000	0.0000	437.0100
x_4	293.02	288.8400	288.8400	346.6000
x_5	138.14	138.1399	138.1399	165.7600
x_6	0.50	0.0000	0.0000	0.0000
x_7	586.04	586.0400	586.0400	703.2400
d_1	83.72	590.2200	590.2200	271.2700
d_2	192.56	0.0000	0.0000	0.0000
d_3	175.81	0.0000	0.0000	437.0100
d_4	108.84	108.8400	108.8400	130.6000
d_5	71.16	138.1399	138.1399	165.7600
d_6	96.28	117.2000	117.2000	140.6800
d_7	25.12	25.1200	25.1200	30.1000
d_8	807.90	812.0798	812.0798	974.4897
d_9	4.19	0.0000	0.0000	0.0000
d_{10}	4.19	234.4200	234.4200	281.2600
d_{11}	87.91	0.0000	0.0000	0.0000
d_{12}	58.60	0.0000	0.0000	0.0000
d_{13}	154.88	154.8800	154.8800	185.9000
d_{14}	66.98	0.0000	0.0000	0.0000
d_{15}	0.50	0.0000	0.0000	0.0000
Ee_1	1272.54	1272.5400	1272.5400	1522.0300
Ee_2	133.95	133.9500	133.9500	160.7400
Ee_3	581.85	586.0400	586.0400	703.2400

* Energy is measured in Petajoules (PJ).
** Source: Department of National Development and Energy (1983).

Table 2. Optimum Activities for AEPSOM (PJ)* 1989–1990

		Model Solution	
Energy Type	Forecast*	Existing ± T Model Solution No. 1	Optimum ± T Model Solution No. 2
R_1	4198.56	4198.5596	4198.5596
R_2	1159.52	0.0000	649.5796
I_{e1}	326.51	648.8518	0.0000
R_3	933.48	933.4800	933.4800
R_4	58.60	86.6100	86.6100
R_5	171.63	171.6301	171.6301
R_6	1.00	1.0000	0.0000
R_7	4299.02	4299.0195	4299.0195
RR_1	0.00	0.0000	0.0000
E_1	1272.54	769.2666	768.2666
E_3	133.95	0.0000	0.0000
E_4	58.60	86.6100	86.6100
x_1	594.42	3429.2935	3430.2935
x_2	1172.08	360.0001	360.0002
E_2	8.37	288.8523	289.5797
x_3	523.25	933.4800	933.4800
x_4	447.90	330.2300	330.2300
x_5	171.63	171.6301	129.7701
x_6	0.00	0.0000	41.8600
x_7	1.00	1.0000	0.0000
x_8	4299.02	4299.0195	4299.0195
d_1	125.61	909.3228	910.3228
d_2	96.28	0.0000	0.0000
d_3	318.14	698.5671	697.5671
d_4	171.63	100.0000	100.0000
d_5	104.65	0.0000	0.0000
d_6	123.58	255.3500	255.3500
d_7	41.86	0.0000	0.0000
d_8	4.19	0.0000	0.0000
d_9	891.62	0.0000	0.0000
d_{10}	0.00	41.8599	0.0000
d_{11}	4.19	0.0000	0.0000
d_{12}	0.00	0.0000	41.8600
d_{13}	4.19	0.0000	0.0000
d_{14}	66.98	0.0000	0.0000
d_{15}	125.58	95.4399	138.2999
d_{16}	230.23	230.2300	230.2300
d_{17}	66.98	171.6301	129.7701
d_{18}	0.00	1.0000	0.0000
Ee_1	2519.97	2519.9702	2519.9702
Ee_2	104.65	104.6500	104.6500
Ee_3	246.97	246.9700	246.9700
Ee_4	4299.02	4299.0200	4299.0200